

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 08 DEC 98	3. REPORT TYPE AND DATES COVERED FINAL 1 Jun 98 - 30 NOV 98
4. TITLE AND SUBTITLE Long Life Thermal Battery for Sonobuoy		5. FUNDING NUMBERS N00167-98-C-0038
6. AUTHOR(S) Thomas D. Kaun		
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) InvenTek Corporation 320 Willow Street New Lenox, IL 60451		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES) Carderock Division Naval Surface Warfare Center 9500 MacArthur Blvd. West Bethesda, MD 20817-5700		10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

19981218 079

a. DISTRIBUTION / AVAILABILITY STATEMENT

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13. ABSTRACT (Maximum 200 words)

Report developed under SBIR contract: The Phase I work provided a proof-of-concept for a long life thermal battery. Life of the state-of-the-art thermal battery is extended from 2.5 to 6.0 hours for sonobuoy application to meet advanced development objectives. As proposed, long life is accomplished by significantly improved heat retention using vacuum/multifoil insulation rather than Microtherm insulation. First, the work evaluated a battery mockup with an actual battery case and its Microtherm insulation components. Its cooling profile simulated the actual battery's time at operating temperature. This battery mockup, using the same header, was then placed into the vacuum/multifoil (V/M) insulated battery case. The battery mockup within the V/M insulation has its cooling profile extended more than two fold; temperature decrease per hour for the V/M insulation was about 40% of the conventional Microtherm insulation. Also, as calculated by our detailed spreadsheet model, 75% of the heat loss in the V/M case mockup came from the header. The SBIR gave proof-of-concept to other advanced battery features. 1) A ceramic-fiber separator exhibited improved handling properties and also gave comparable cell performance to MgO powder. The fiber separator may reduce cost of manufacturing the battery. 2) An alternative cell chemistry with $\text{FeS}_2\text{-CuFeS}_2$ cathode showed 50% increased peak power. Cell tests were conducted at 480°C to provide a comparison with a baseline CoS_2/LiSi cell design using $0.9\text{A}/\text{cm}^2$, 10-sec power pulses over a 6-h period. The results show the feasibility of a thermal battery with a 6-h life, as required of the battery for an advanced sonobuoy. Also, a live thermal battery test, although of a different size, exhibited more than a doubling of operating life due to the superior heat retention afforded by V/M insulation. Additionally, higher power/energy designs of interest to the Navy can be approached with the innovative thermal battery components given proof of concept in this phase I SBIR.

14. SUBJECT TERMS SBIR report; Proof of concept for 6-hour (long life) thermal battery for advanced sonobuoy. Improved energy/power		15. NUMBER OF PAGES
		16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED
20. LIMITATION OF ABSTRACT UL		

Final Report for Phase I (June 1 – November 30, 1998)
Navy Small Business Innovative Research
“ Long Life Thermal Battery for Sonobuoy”
Contract #N00167-98-C-0038

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Abstract - Phase I Final Report

The Phase I work provided a proof-of-concept for a long life thermal battery. Long life is in reference to extending life of the state-of-the-art thermal battery for sonobuoy application from 2.5 to 6.0 hours to meet advanced development objectives. As proposed, long life is accomplished by significantly improved heat retention using vacuum/multifoil insulation rather than Microtherm insulation.

First, the work evaluated a battery mockup with an actual battery case and its premium thermal-insulation components. Its cooling profile simulated the actual battery's time at operating temperature. This battery mockup, using the same header, was then placed into the vacuum/multifoil (V/M) insulated battery case. The battery mockup within the V/M insulation has its cooling profile extended more than two fold; temperature decrease per hour for the V/M insulation was about 40% of the conventional Microtherm insulation. Also, as calculated by our detailed spreadsheet model, 75% of the heat loss in the V/M case mockup came from the header.

The SBIR gave proof-of-concept to other advanced battery features. 1) A ceramic-fiber separator exhibited improved handling properties and also gave comparable cell performance to MgO powder. The fiber separator may reduce cost of manufacturing the battery. 2) An alternative cell chemistry with FeS_2 - CuFeS_2 cathode showed that 50% increased peak power (e.g. 2.75 W/cm^2 vs. $1.66/\text{cm}^2$) may be obtained for sonobuoy application. Cell tests were conducted at 480°C to provide a comparison with a baseline CoS_2/LiSi cell design using 0.9A/cm^2 , 10-sec power pulses over a 6-h period.

The results show the feasibility of a thermal battery with a 6-h life, as required of the battery for an advanced sonobuoy. Also, a live thermal battery test, although of a different size, exhibited more than a doubling of operating life due to the superior heat retention afforded by V/M insulation. Additionally, higher power and/or higher energy designs of interest to the Navy can be approached with the other innovative thermal battery components given proof of concept in this phase I SBIR.

Introduction

Antisubmarine warfare (ASW) measures remain a critical part of our national defense strategy. The Navy has identified the need for an exponential increase in thermal battery capability to be a shortcoming to fulfilling advanced active sonobuoy performance standards(1). In the past, the Navy's primary thermal battery developer for the sonobuoy battery, Northrop Grumman (NG), Cleveland, OH (now ENSER) has made tremendous strides in increasing performance and life for ERAPSCO (2-4). Issues still remain before system deployment in spite of 6kW/4h thermal battery capability. The NG chemistry, LiSi/CoS_2 , is costly and may have drawbacks for commercialization. In particular, the NG, A-size sonobuoy thermal battery, which uses a mineral insulation Microtherm, has life limited to about 4h and performance capability of 6kW for 200 ping-sec.

With a Phase I SBIR, we saw an opportunity in applying our rechargeable thermal battery (RTB) technology to bring about increased performance, along with extension of operating life to 6-h. The Phase I SBIR evaluated InvenTek component technologies, e.g. super insulation, thin fiber separator, and rechargeable thermal battery technology as they apply to the 'A' size sonobuoy battery. These evaluations provide hard data to enable system optimization with the Shuster Model at NG. In the Phase I option, we will demonstrate battery designs that are attractive from the optimization modeling results. The primary objective is extending operation time to about 6 h, but we see excellent prospects to concurrently increase thermal battery pulse power/energy by 50%. Through discussion with our Technical Rep., Peter Keller, and phone conferences with interested parties, the 6-h goal for the SBIR became the focus of our effort with a new 6-h life requirement for the thermal battery.

Phase I Results and Discussion

Task 1: Develop and evaluate super insulation (vacuum/multifoil, V/M) for thermal battery application.

Objective: Proof-of concept for a 6h life for the thermal battery of an 'A' size sonobuoy is provided with a Vacuum/ Multifoil (V/M) insulated case. Using a battery mock up test having an Al block thermal mass and standard header, Ron Guidotti, SANDIA, conducted the thermal-loss tests initially with the standard Microtherm case. This standard battery mockup simulates the 2.65-h battery life that is generally obtained. Now, cooling profiles from 525°C for the first V/M sonobuoy-battery case extended time at operating temperature to 6 hours. (The project is subsidized by a \$5K test grant under the DOE small business initiative program, SBI #3303.)

V/M case design

Based on the available information, V/M case development and fabrication has proceeded with commercially-available parts for the size 'A' sonobuoy battery. The first sonobuoy V/M case is considered a test vehicle, which approximates the critical dimensions of the actual battery case, i.e. its ID is such that comparisons to other types of insulation can be made. The V/M insulation is a double-walled vessel. A heavier outside wall should not impact the results of the calorimetric evaluations that are planned; the inner wall is dimensioned to readily accept the sonobuoy battery and retrofit to the current battery case. Additionally, the inner sleeve can also accept the 250 lb

compressive load which is used to assemble the battery. The inner sleeve is cantilevered from a substantial welding ring at the mouth of the case. Figure 1 is a drawing of the V/M case that has been produced. The case is V/M insulated on the bottom, as well as the side walls. To minimize heat loss along the inner sleeve at the header, its cross-section is reduced (see detail on drawing 1). Future battery cases would use thin, deep-drawn inner sleeve to accomplish this feature. The first V/M case is also produced by conventional processing and will serve as a benchmark for our continued development.

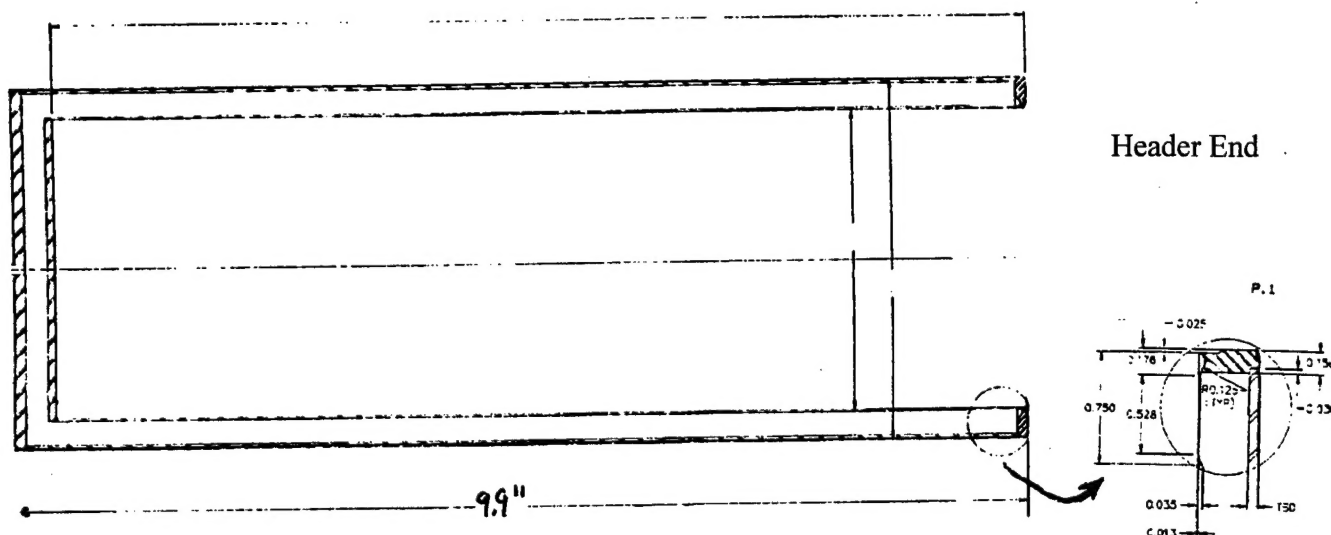


Fig. 1, the V/M case is insulated on the bottom, as well as the sidewalls. To minimize heat loss along the inner sleeve, its cross-section is reduced at the header (see detail).

V/M case testing

The project with Ron Guidotti at SANDIA has conducted the thermal-loss tests for the simulated, sonobuoy-battery. The thermal mass of the battery is simulated with a 3.25 kg block of Al with heating rods inserted (see Fig.2). Calorimetric evaluations of V/M insulation relative to the conventional Microtherm insulation use actual battery cans and Microtherm parts that were obtained from NG. The cooling curve for the mockup of the sonobuoy thermal battery using the standard Microtherm insulated case has a temperature drop of about 1°C/min, or 150°C in 150 min. The thermal mass is heated to 525°C and held 15 min before allowed to cool. This battery mockup exhibits about a 2.5 h battery life, that is time at operating temperature above 360°C.

This battery mockup is now applied to the V/M battery case. Calorimetric evaluations of V/M insulation relative to the conventional Microtherm insulation use actual battery cans and Microtherm parts, as in the header, that were obtained from NG. The cooling curves for the mockup of the sonobuoy thermal battery using the V/M case and the standard Microtherm-insulated case are presented in Fig. 3. In both tests, the thermal mass is heated to 525°C and held 15 min before allowed to cool. Temperature drops at 27 °C/h, or 165 °C in 6-h. This battery

mockup with the V/M battery case exhibits about a 6-h battery life, that is time at operating temperature above 360°C . On the other hand, the conventional Microtherm insulation temperature drops at 62°C/h , or 165°C in 2.65-h.

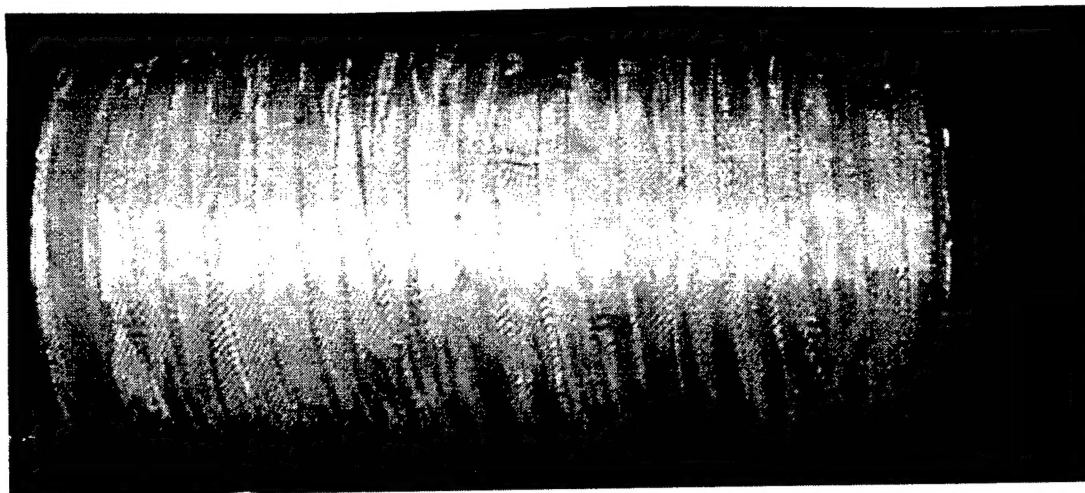


Fig.2, The thermal mass of the thermal battery is simulated with a 3.25 kg block of Al with heating rods inserted.

Temperature of Al Block with Microtherm and Vacuum Multifoil Insulation During Cooling from 525°C

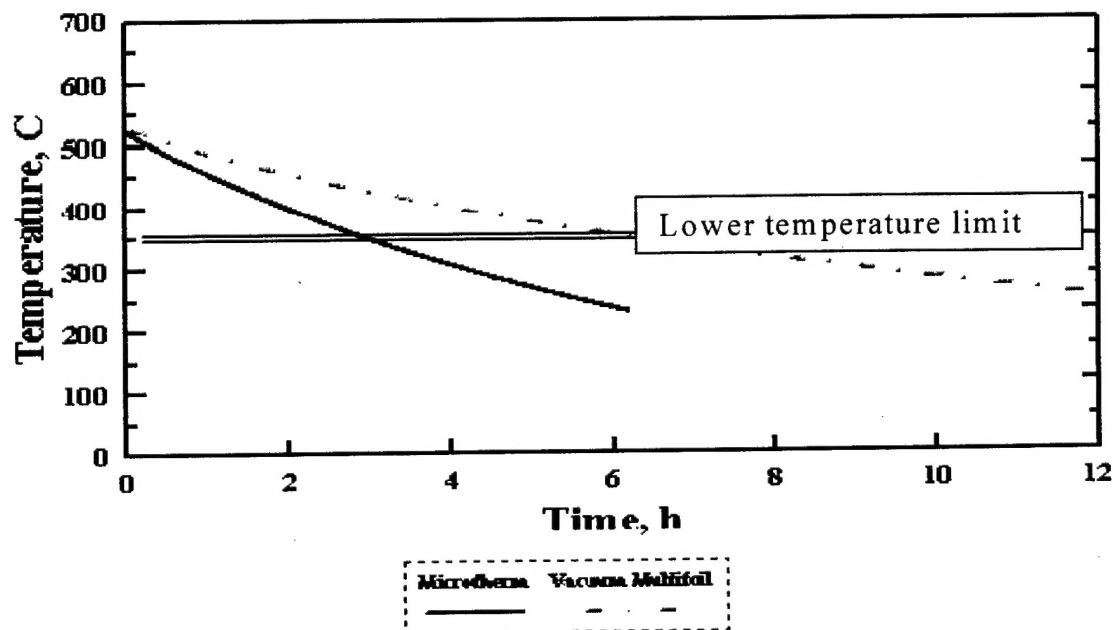


Fig. 3, Comparison of the internal temperature of the Al block cooling from 525°C using case insulated with Microtherm and vacuum/multifoil. The cooling of the Microtherm case is similar to the 2.65 h life of an actual sonobuoy battery (i.e. 525 to 365°C). With the vacuum/multifoil case, operating-life is extended to 6-h.

Steady-state heat loss measurements provided data relating heat loss as function of temperature, ie. higher heat loss rates at higher temperature. External temperature for the V/M case was generally 75 °C cooler, that is 50°C vs. 125 °C at 525 °C battery temperature. Heat loss for the V/M case mockup is dominated by the header. Since the heat losses from the sides and bottom were dramatically reduced in the case of the vacuum /multifoil container, the heat losses were greater from the header end. The steady-state temperatures for the vacuum/multifoil case showed more hysteresis than did those for the case with Microtherm insulation, because of the slower rate of heat loss. This resulted in much longer equilibration times to reach a pseudo-state temperature. Most of the data was taken after two hours of equilibration and the data would show better agreement if the waiting period had been 4-6 h. Details of these tests follow. These values will be used in design calculations for the phase I option effort.

Fig. 4, **Steady-State Midcase Temperatures with Microtherm Sleeve and Vacuum Multifoil as a Function of Internal Block Temperature**

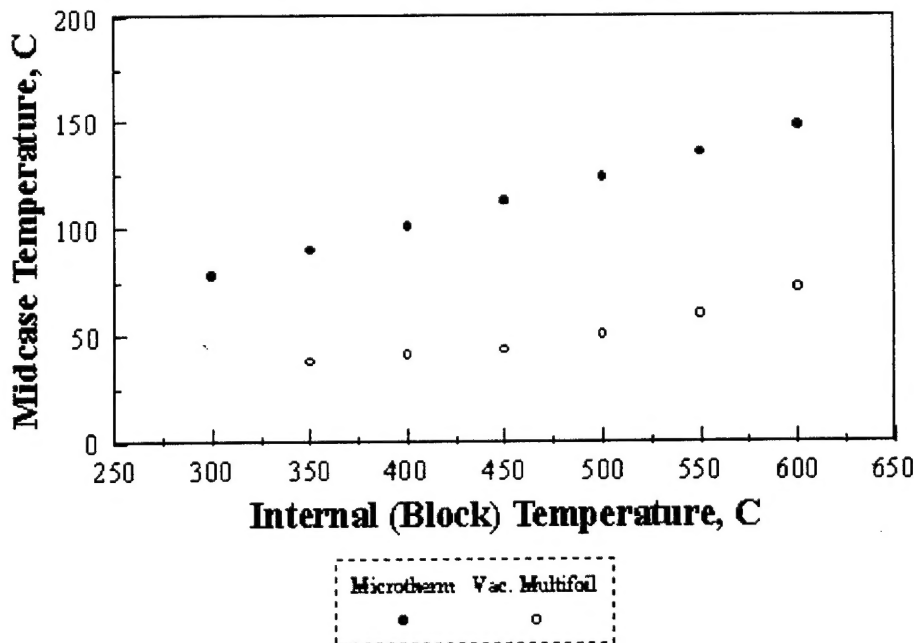


Fig. 5, Steady-State Bottom Temperatures with Microtherm Sleeve and Vacuum Multifoil as a Function of Internal Block Temperature

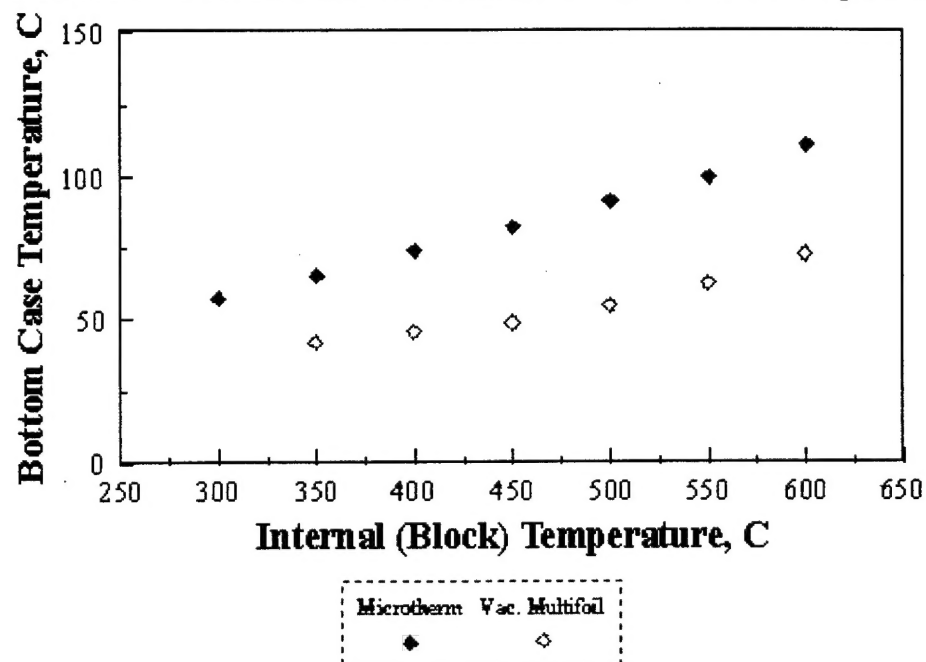
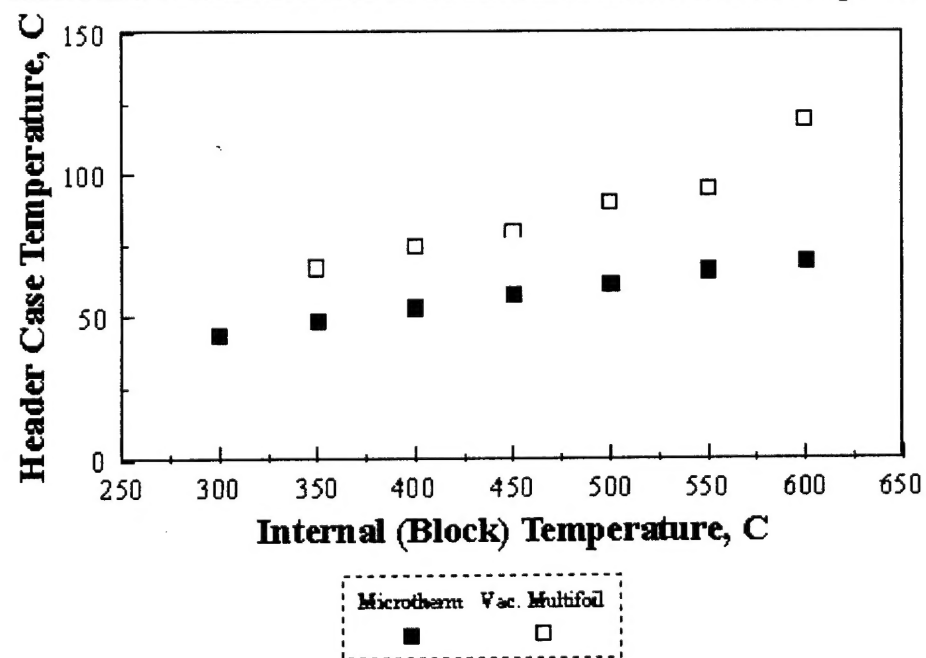


Fig. 6, Steady-State Header Temperatures with Microtherm Sleeve and Vacuum Multifoil as a Function of Internal Block Temperature



A detailed heat-loss calculation was carried out using the design dimensions as presented above. As in Table 1, 75% of the battery's heat loss is calculated to come from the header (conventional-insulated) of a V/M insulated thermal battery. To minimize heat loss along the inner sleeve at the header, its cross-section is reduced (see detail on drawing 1). Future battery cases would use thin, deep-drawn inner sleeve to accomplish this feature. We anticipate further reductions in heat loss may come from improved header design. We would proceed by running mockup tests of proposed design modification.

Table 1, Heat loss calculations for sonobuoy battery in V/M insulated case

Heat Loss Through Cover	
<u>Heat Loss Through Cover Sidewall</u>	
Vessel interior diameter, cm	9.911
Wall thickness, cm	0.033
Wall area, cm ²	1.025
Length of heat transfer path, cm	1.27
Interior temperature, °C	500
Exterior temperature, °C	100
Conductivity of stainless steel at 300°C, W/cm-°C	0.189
Heat loss, W	61
Fraction of total cover loss, %	72
<u>Heat Loss Through Insulation</u>	
Insulation thickness, cm	1.27
Insulation diameter, cm	9.906
Area, cm ²	77.1
Conductivity of insulating material, W/cm-°C	0.00087
Heat loss, W	21
Fraction of total cover loss, %	25
<u>Heat Loss Through Leads</u>	
Lead Length, cm	5
<u>Lead Cross-Section</u>	
Maximum current, A	60
Voltage loss through each lead at max current, V	0.2
Copper lead resistivity at 300°C, microhm-cm	3.6
Cross-section, cm ²	0.005361
Thermal conductivity of copper at 300°C, W/cm-°C	3.67
Fraction of total cover loss, %	4
Heat loss, W	3
<u>Total Heat Loss, W</u>	85

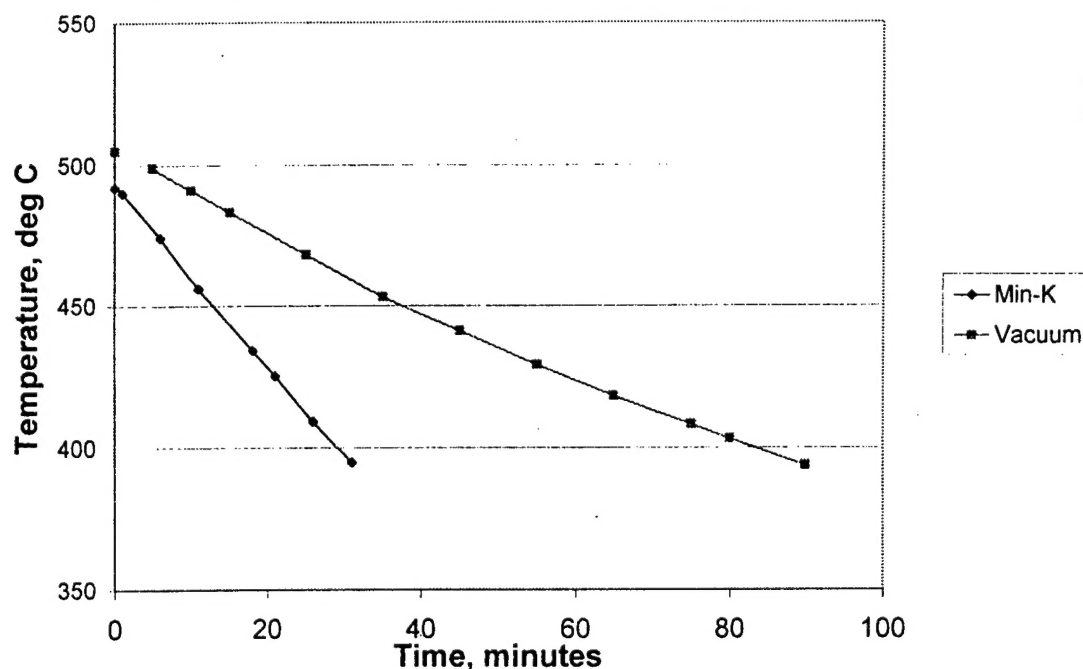
Exploratory test of thermal battery in a Vacuum/ multifoil insulated case

A vacuum-multifoil, V/M, case having a 2.55 in. ID X 0.22 in. wall. The vacuum annulus is no more than 0.15". Its annulus contains only 3 foils, (vs. 15 for the case that is sized for the sonobuoy battery). Although it is not sized for a sonobuoy battery, eg. 4 in. ID, this case provides anticipated information on extending thermal battery life by improved heat retention.

Prior to the live thermal battery test, we simulated heat loss from two types of insulation, each about 0.25" thick. They are V/M and MinK (comparable to microtherm). An 8 inch long Aluminum mass with a rod heater simulated the battery's thermal mass. Both tests used 0.5" thick Min K blanket as a header piece. In each task, the thermal mass was heated to 500 – 525°C in 30-45 min, and stabilized at that temperature for 5-10 min, before the cool-down was logged. At the stabilized temperature, the skin temperature of the V/M case was virtually unchanged at 26°C,

while the skin temperature of the MinK insulated case was 156°C. This striking difference is indicative of the superiority of the V/M insulation. The dominant heat loss for the V/M insulation was at the "make-shift" header where the temperature rose to 46°C during the extended cool down phase. Fig. 7 shows the cool down of the simulated battery within the two types of insulation, each only 0.25" thick. As seen, the V/M insulation maintains battery temperature in the operating range 500 – 425°C, about 3 times longer. These are encouraging results for extending sonobuoy battery life to 6h. The actual sonobuoy battery has greater thermal mass and will use thicker insulation.

Fig. 7. **Cool Down For Two Types of Insulated (0.25" thick) containers, for 2.5" dia X 8" long battery**



The V/M case was taken to ENSER. At ENSER, a scaled-down JDAM-type thermal battery (75% of design) was assembled in a smaller-than-normal-diameter battery-can to permit a test without its typical insulation. This battery was then slid into the available V/M case (not designed for battery operation). JDAM is designed as a short duration battery (about 180 seconds). The test was also not typical of JDAM. We used spaced-out pulses (4A for 10 sec every 5 min) to track operability of the thermal battery over an extended period to preserve battery capacity.

Thermal and operation data are presented in Figs. 8 and 9. This reduced-size battery only reached 380°C after initiation. Excellent heat retention was demonstrated. The battery temperature fell off at just under 40°C/hour; with the outer-skin temperature of the case rising slowly from 26 to 30°C after 2 h. Nonetheless, the battery produced stable power pulses to near full discharge capacity through 2 hours before electrolyte freezing at 310°C. These are encouraging results for extending sonobuoy battery life to 6h. The actual sonobuoy battery has greater thermal mass and will use thicker insulation.

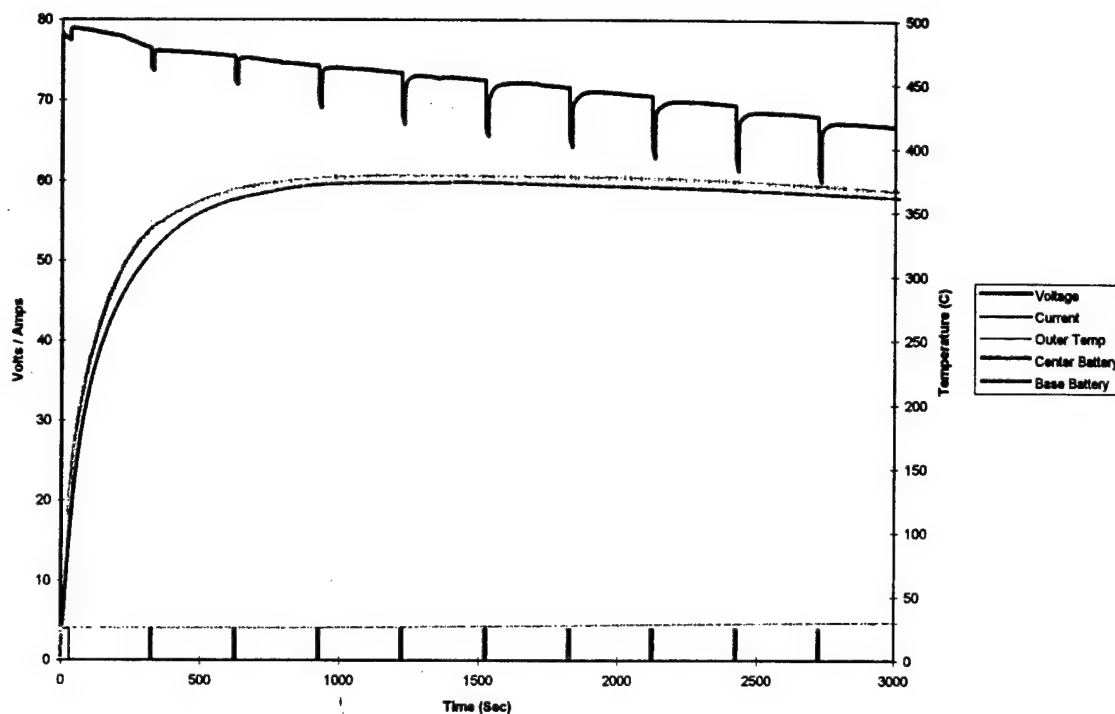


Fig. 8, Thermal and operation data, 0-3K sec, of a non-typical of JDAM thermal battery in V/M insulation; pulses (4A for 10 sec every 5 min) tracked operability for 2 h.

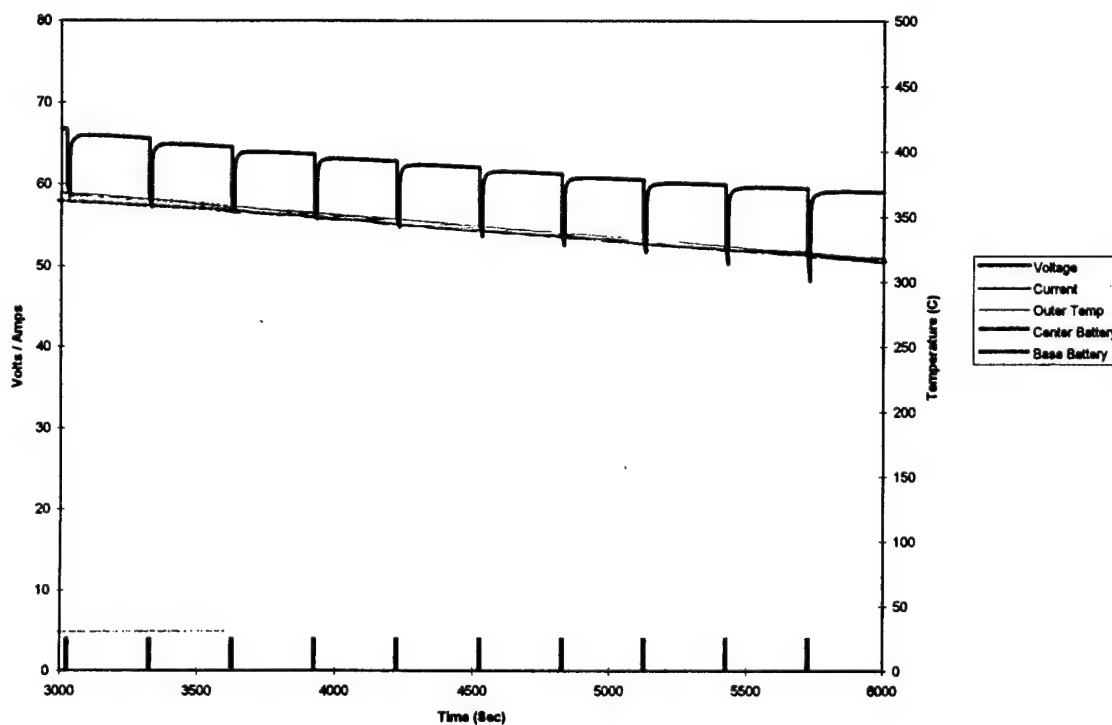


Fig. 9, Thermal and operation data, 3-6K sec, of a non-typical of JDAM thermal battery in V/M insulation; pulses (4A for 10 sec every 5 min) tracked operability for 2 h.

Task 2: Develop and evaluate thin fiber separator

Objective: The viability of the ceramic fiber separator (CFS) is demonstrated for thermal battery with sonobuoy battery components. Comparative tests were conducted with ENSER/NG-provided LiSi/CoS₂ electrode pellets.

To develop the ceramic fiber separator (CFS) for thermal battery, a series of six cell tests examined electrolyte wetting and retention. Initially, the ceramic fiber was viewed as an augmentation to MgO powder separator. Prior to the availability of LiSi anode and CoS₂ cathode, these LiSi/FeS₂ cells (2.25 inch dia electrodes supplied by ENSER) demonstrated the stability of CFS on its own and compared its performance for thermal battery to the MgO powder separator. The prewetting and amount of electrolyte loaded for CFS provided a basis for subsequent development. Some cells operated well with 24% less total electrolyte and almost 50% less separator weight.

Subsequent development used LiSi anode and CoS₂ cathode that were supplied by NG/ENSER for sonobuoy, (although from old leftovers). The ceramic fiber separator is 0.32 mm thick, about 50% less than the MgO separator thickness of the current sonobuoy battery, and has a fine pore structure for good particle retention. It is sufficiently durable in a 9.25 cm dia to pass the "drop" test and has superior handling qualities compare to standard MgO powder/salt pressed pellet. Additionally, we found in these tests that it readily wets with molten salt. Electrolyte was melted into the paper-like CFS separator before assembly. The CFS of 9.25 cm dia was 1.68g and was loaded with 3.5g of LiCl-LiBr-KBr electrolyte. Resistance heaters brought the test cells up to the 450°C operating temperature. No lag in cell voltage vs temperature was noted during heat up indicating adequate cell initiation with CFS. Good chemical stability of the separator was shown by stable cell voltage for greater than 24 hours after initiation. In Fig.10, the first test with LiSi anode, CoS₂ cathode, and the CFS, the cell gave expected full discharge capacity of 3.5 Ah with 15 A 30 sec pulses. Again, these cells operated well with 24% less total electrolyte and almost 50% less separator weight.

The second cell test, Fig. 11, examined the standard MgO powder/salt (as in pressed pellet) separator. The performance/stability of this cell was somewhat better than the first cell with the CFS. The cell shows a lower impedance than the CFS during the early part of the discharge capacity that increases during the discharge. These preliminary tests indicate the viability of the CFS, that is prewetted with electrolyte. It performs quite well without any additions of MgO, and anticipate that the CFS will operate slightly better with added salt. We find that weight/thickness of the separator may be reduced by 50% with the CFS.

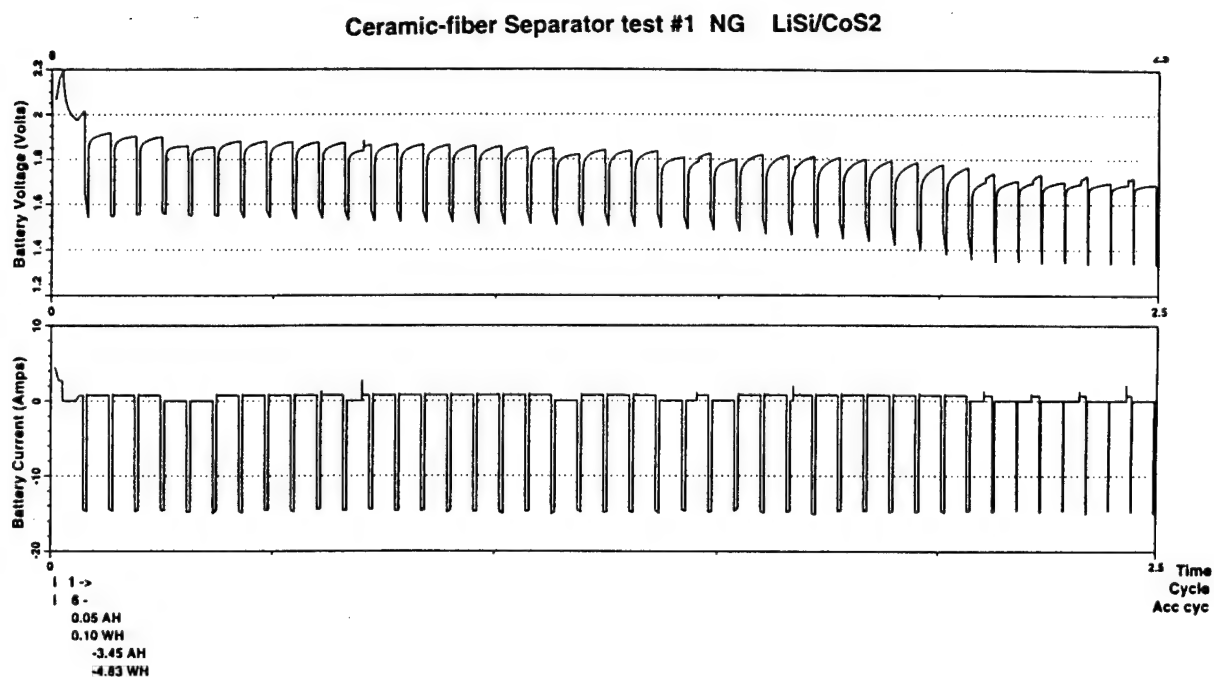


Fig.10, the first CFS test with LiSi anode, and CoS₂ cathode; the cell gave expected full discharge capacity of 3.5 Ah with 15 A 30 sec pulses (every 5 min).

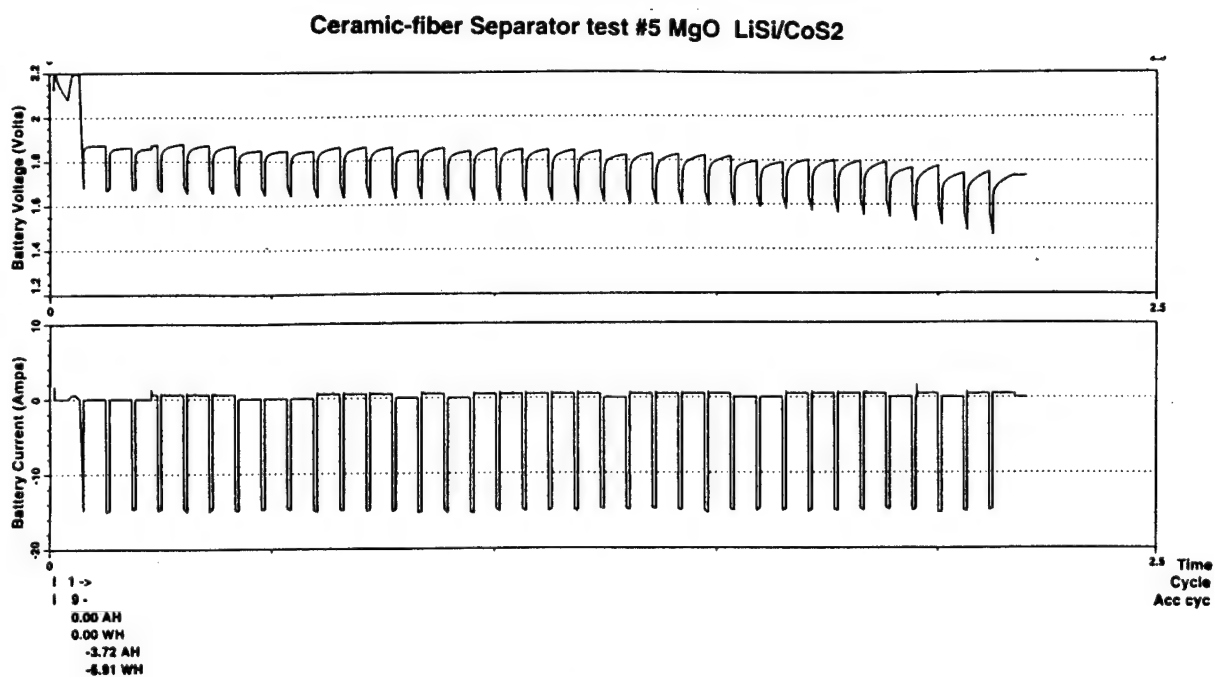


Fig. 11, examined the standard MgO powder/salt (as in pressed pellet) separator with LiSi anode, and CoS₂ cathode with testing as above

Subsequently, the ceramic fiber separator (CFS) was tested at full power (50 A pulses for 10-s) using LiSi anode and CoS₂ cathode as supplied by NG/ENSER for sonobuoy thermal battery. Without prior test experience, each successive test examined higher pulse power levels. The baseline test cell #5, with LiSi anode, CoS₂ cathode, and MgO pressed-powder (10.7 g), gave expected full discharge capacity of 3.5 Ah using 25A 20 sec pulses at about 1.3 V, while at full power with 50 A -10 sec pulses at 1.17 V, in Fig. 12. Significant performance improvement resulted from increasing the electrolyte content of the CFS for thermal battery test. The ceramic fiber separator is 0.32 mm thick, about 50% less than the MgO separator thickness of the current sonobuoy battery. Electrolyte was melted into the paper-like CFS separator before assembly. The CFS of 9.25 cm dia was 1.68 g and was loaded with 5.25 g of LiCl-LiBr-KBr electrolyte, or about 50% more than in the first test. Resistance heaters brought the test cells up to the 450°C operating temperature. By comparison, the ceramic fiber separator (CFS) was examined with 12% less total cell electrolyte and almost 30% less separator weight. As in Fig. 13, the CFS cell #6 shows somewhat better performance than the baseline cell with 25 A 20 sec pulses at about 1.5 V. Then with 50A- 10 sec pulses, the cell voltage is 1.25 V. The cell #6 impedance 12 milliohm, or 0.79 ohm cm², is somewhat lower than the baseline #5 at 13 milliohm, or 0.86 ohm cm².

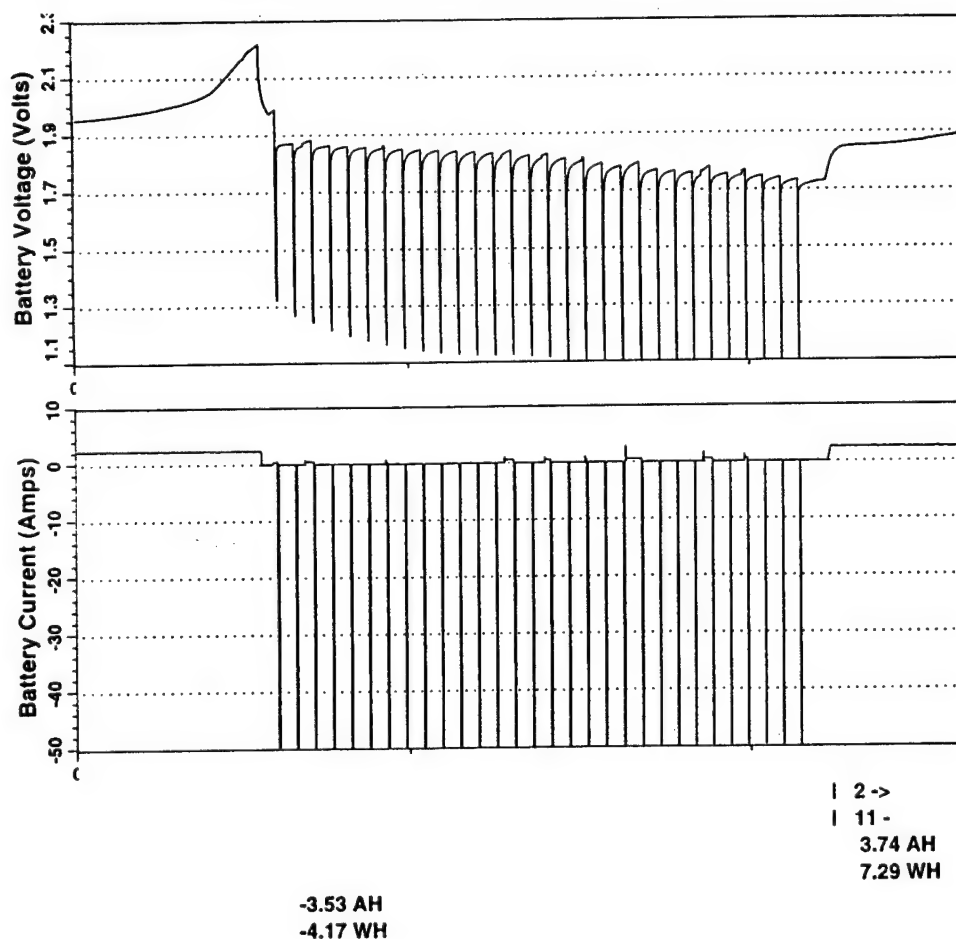


Fig. 12, examined the standard MgO powder/salt (as in pressed pellet) separator with LiSi anode, and CoS₂ cathode; testing with 50 A, 10 sec pulses (every 5 min). gave expected full discharge capacity of 3.5 Ah.

Ceramic-fiber Separator test #6 CFS LiSi/CoS₂

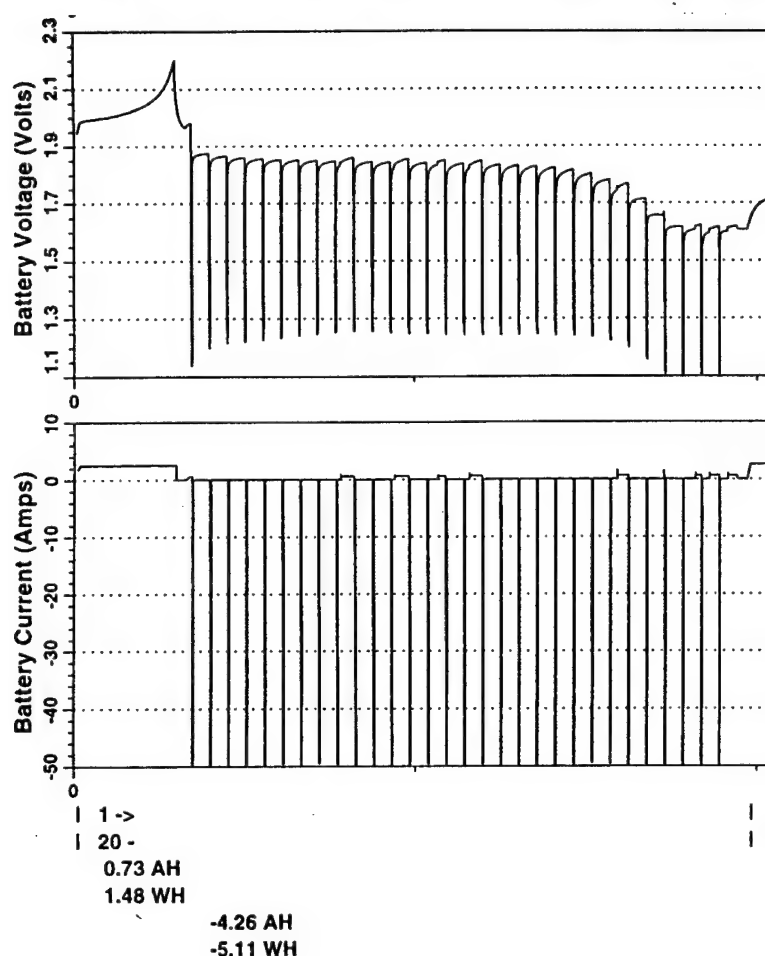


Fig.13, the second CFS test with LiSi anode, CoS₂ cathode, and CFS that is 50% thickness of the MgO; the cell also gave expected full discharge capacity of 3.5 Ah with 50 A, 10 sec pulses (every 5 min) and at somewhat higher voltage 1.25 V.

A second type of ceramic fiber separator (CFS) was tested at full power (50 A pulses for 10 s) using LiSi anode and CoS₂ cathode as supplied by NG/ENSER for sonobuoy thermal battery. It compared favorably with the baseline test cell #5, with LiSi anode, CoS₂ cathode, and MgO pressed-powder (10.7 g). As in Fig. 14, test cell #7 gave expected full discharge capacity of 3.5 Ah at full power with 50 A -10 sec pulses at 1.21V, compared to 1.17 V for cell #5. This ceramic fiber separator is 0.5 mm thick. Also, using the "drop" test, this CFS is sufficiently durable in a 9.25 cm dia. size. Electrolyte was melted into the paper-like CFS separator before assembly. The CFS of 9.25 cm dia was 1.68 g and was loaded with 8.5 g of LiCl-LiBr-KBr electrolyte. Resistance heaters brought the test cells up to the 450°C operating temperature.

Ceramic-fiber Separator test #7 CFS w/1 LiSi/CoS₂

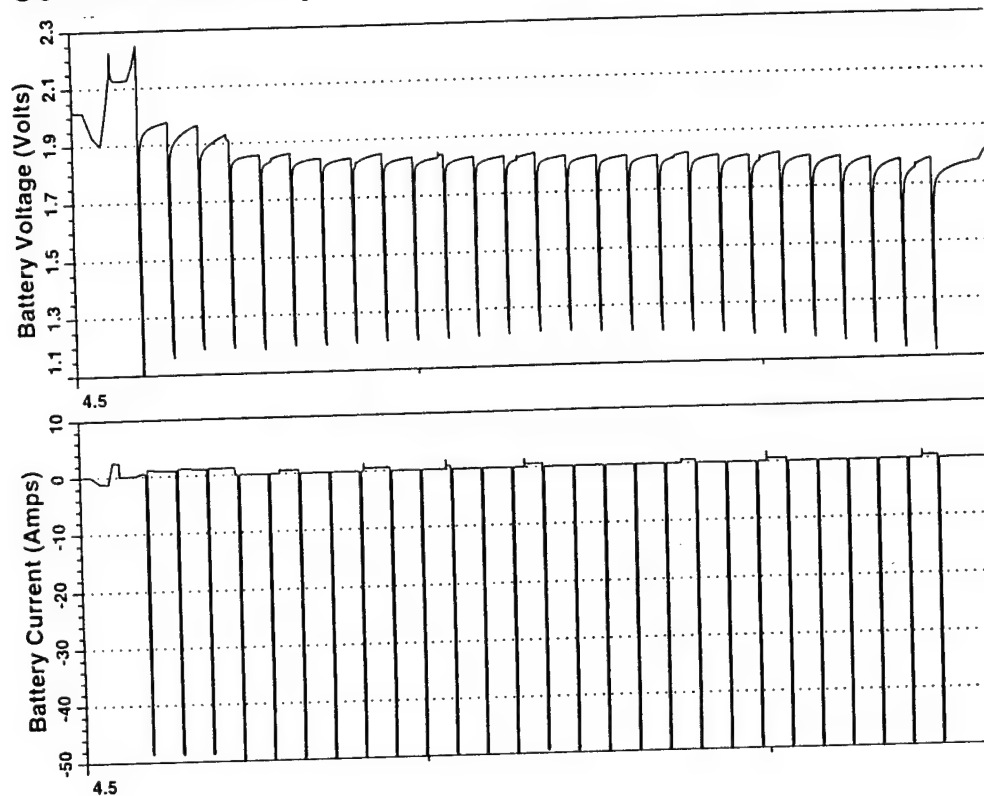


Fig. 14, test cell #7, a second type of ceramic fiber separator (CFS), gave expected full discharge capacity of 3.5 Ah at full power with 50 A -10 sec pulses at 1.21V

These tests at full power indicate the viability of the CFS that is prewetted with electrolyte. The CFS performs as well or better than the baseline separator. We find that weight/thickness of the separator may be reduced by 30% with the CFS. For battery design, actual parts are critical to the success of this task. In the context of the 6h battery-life requirement, the thin fiber separator can enable tradeoffs in component thickness to maintain battery capacity, reduce cell self-discharge rate, and improve separator handling-properties. We have supplied Nick Papadakis at NG with CFS to replicate test conditions previously-used for sonobuoy battery development.

Task 3: Adapt and test rechargeable thermal battery (RTB) technology to the sonobuoy application.

Objective: Improved power-pulse performance is demonstrated. Comparative tests with the rechargeable chemistry $\text{FeS}_2\text{-CuFeS}_2$ with LiI were conducted at ENSER/NG and showed as much as 50% reduced cell impedance vs. the standard chemistry. These tests suggest that 50% higher peak power density can be obtained by a thermal battery for sonobuoy application.

Improved pulse power performance for a sonobuoy battery was demonstrated at NG/ENSER with the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry having a LiI modified electrolyte. The electrodes were pressed with the approximate weight and thickness for sonobuoy. Comparative tests at 480°C provided encouraging results; cell impedance at full power was typically about 50% of the LiSi/CoS_2 . As in Fig. 15, the final voltage from the power pulses is higher with the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry (Inventek14) than the baseline LiSi/CoS_2 (Inventek02). These tests used 32 cm^2 pellets with the typical 0.9 A/cm^2 current density for 20 pulses at 10 sec over a 6-h period. As in Fig. 17, baseline cell gave a typical $0.45\text{-}0.56\text{ ohm/cm}^2$ impedance ($\Delta V/I$); while in Fig. 16, the rechargeable chemistry has an impedance of only $0.28\text{-}0.39\text{ ohm/cm}^2$. Using the 1.8 V open-circuit value, peak power for $\text{FeS}_2\text{-CuFeS}_2$ chemistry is typically 70% higher than the CoS_2 chemistry; that is, 2.75 W/cm^2 vs. 1.63 W/cm^2 . In the context of the 6h battery-life requirement, extension of battery operation to lower temperature is anticipated. Tradeoffs in performance can be considered with higher specific energy and pulse power of the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry with LiI modified electrolyte, or more ping-sec. That is, a fewer number of cells may be used. Finally, the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry has lower cost prospects.

Earlier an attempt confirmed the improved pulse power performance of the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry having LiI modified electrolyte. It used salvaged electrode pieces from rechargeable cells. The electrode pieces were thicker than those for sonobuoy, but the MgO separator had been received from NG. This crude test also provided at 450°C encouraging results; cell impedance at full power was only about 50% of the LiSi/CoS_2 , or 0.4 ohm cm^2 .

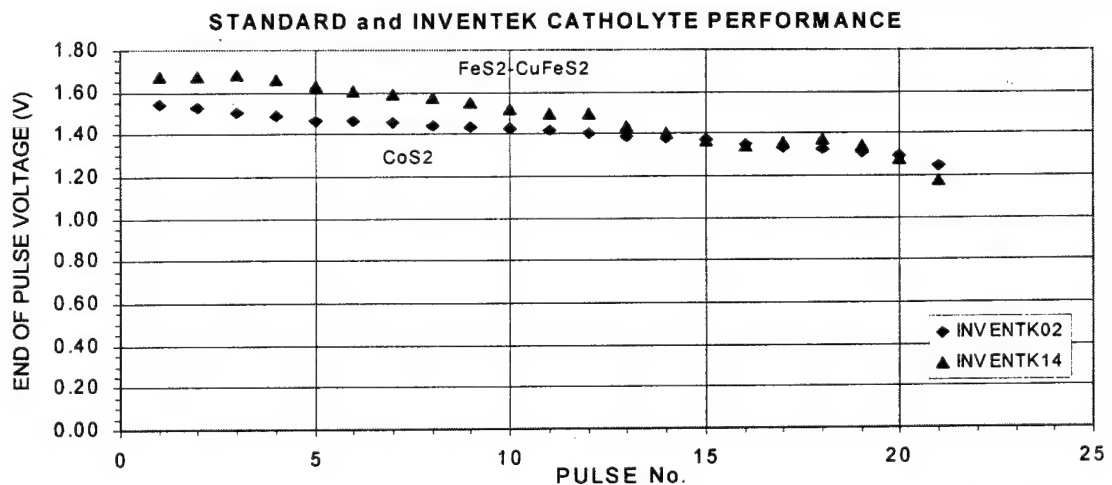


Fig. 15, the final voltage from the power pulses (0.9 A/cm^2 current density) is higher with the $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry (Inventek14) than the baseline LiSi/CoS_2 (Inventek02).

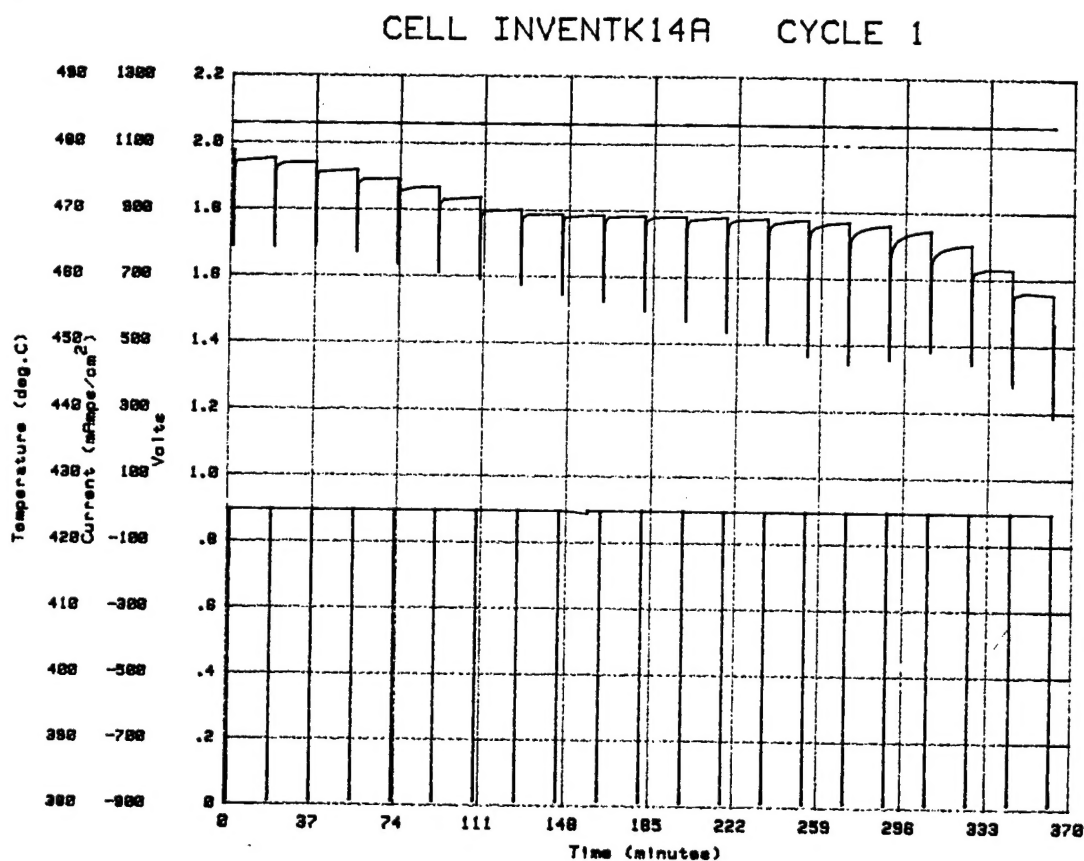


Fig.16, Voltage/time plot of $\text{LiAl/FeS}_2\text{-CuFeS}_2$ chemistry having a LiI modified electrolyte. Tests at 480°C used 32 cm^2 pellets with the typical 0.9 A/cm^2 current density for 20 pulses at 10 sec over a 6-h period, gave a $\Delta V/I$ of $0.28\text{-}0.39\text{ ohm/cm}^2$

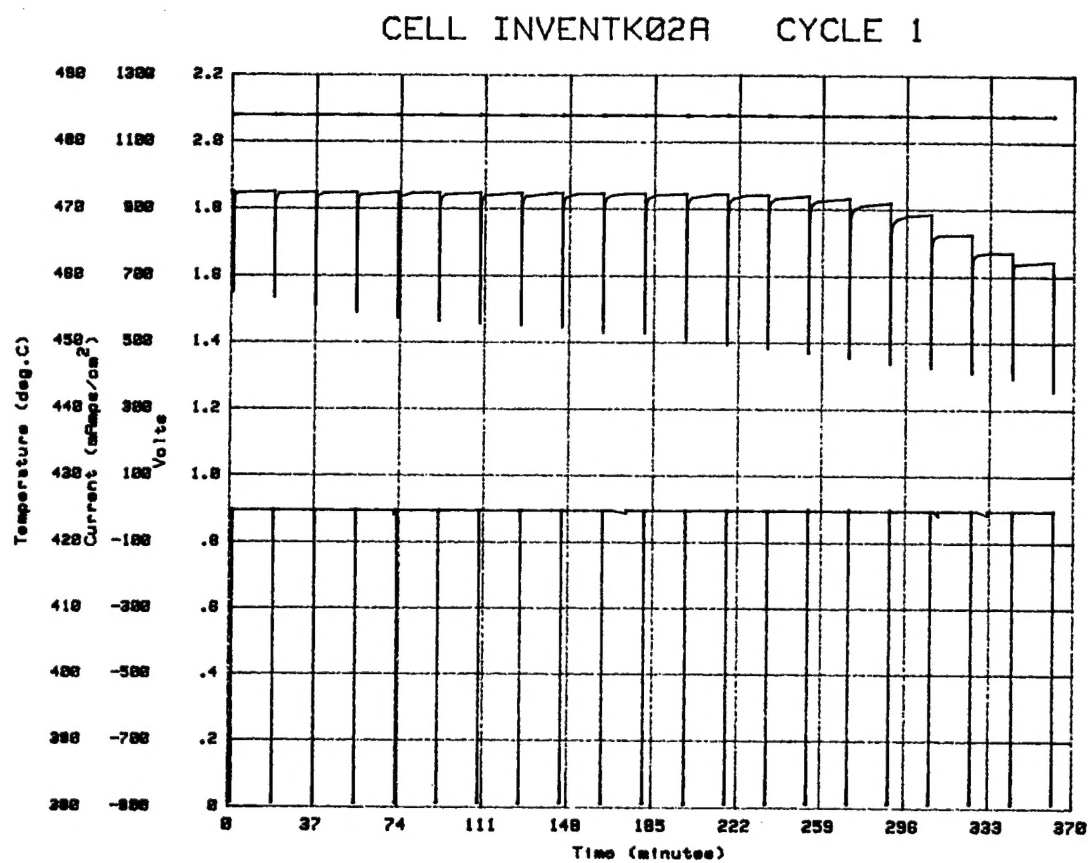


Fig. 17, Voltage/time plot of baseline LiSi/CoS₂ cell gave a typical 0.45-0.56 ohm/cm² impedance ($\Delta V/I$)

Conclusions and Future Work

The Phase I work provided a proof-of-concept for a long life thermal battery. Long life is in reference to extending life of the state-of-the-art thermal battery for sonobuoy application from 2.5 to 6.0 hours to meet advanced development objectives. As proposed, long life is accomplished by a significantly improved heat retention using vacuum/multifoil insulation rather than Microtherm insulation. First, the work evaluated a battery mock up (Al block with rod heaters) with an actual battery case and its Microtherm insulation components. Its cooling profile simulated the actual battery's time at operating temperature of 2.65-h. This battery mockup, using the same header, was then placed into the vacuum/multifoil (V/M) insulated battery case. The battery mockup within the V/M insulation has its cooling profile extended more than two fold; temperature-decrease/hour for the V.M insulation was about 40% of the conventional insulation.

Steady state heat loss and temperature profiles of the battery at temperatures up to 600°C were taken. The measurements indicate that the header was the primary heat loss for the A-size sonobuoy battery with V/M insulation. This situation is understandable in light of the superior insulating capability of the V/M insulation. The temperature rise at the outside bottom and side of the case was only 20°C above ambient at battery operating temperature, or internal 525°C.

Our spreadsheet calculations of heat loss also indicate that the header end of the battery with V/M insulation is responsible for at least 75% of the battery's heat loss. Our method of battery mockup operation followed by heat loss calculation can avoid trial and error in developing heat management design for increased battery life. Design improvement of the header component is likely to further increase battery life. We may compromise the quality of the V/M insulation to reduce cost, but through design of the overall heat-management package further improve time at operating temperature.

Our success in increasing time at operating temperature for the A-size battery was supported by a live battery test. Although this battery and case are a smaller OD, 2.5" vs. 5.0", the same ratio of decreased heat loss was identified for this V/M insulated case using a battery mock up. Operating time would increase to about 2.5 times. The same 2.5" OD, V/M case was used in a live thermal battery test at ENSER, which also demonstrated significantly increased battery operating life with low heat loss of about 50°C /2h.

In Task 2, our innovative ceramic fiber separator, CFS, has shown proof-of-concept to be a substitute for MgO powder separator in a thermal battery. Two types of CFS were tested; both exhibit improved handling characteristics. Unlike pressed MgO powder separator, full -size, 3.66" dia. separators of 12 mil or 25 mil thicknesses pass the "drop test", and display some physical flexibility. These fiber separators were compared to the MgO powder separator in tests with 50A, 10 sec pulses, and exhibit comparable

cell impedance. The CFS has the prospect of reducing cell thickness and weight, while improving cell power and production cost due to a lowered piece-loss rate.

The SBIR Task 3 tested the rechargeable cell chemistry of $\text{FeS}_2\text{-CuFeS}_2$ positive electrode with electrolyte having LiI addition. It has shown prospects for significantly increasing peak power by 70% under the sonobuoy battery test conditions. Specifically, cell impedance of $0.45\text{-}0.56\text{ ohm/cm}^2$ for the CoS_2 chemistry was reduced to $0.28\text{ to }0.38\text{ ohm/cm}^2$ for the $\text{FeS}_2\text{-CuFeS}_2$ chemistry. The lower cell impedance can be translated into increased peak power of 2.75W/cm^2 compared to 1.63W/cm^2 for the typical CoS_2 cell. The higher peak power could also allow a tradeoff of higher cell capacity for longer life and greater ping-sec operation. Although the Phase II SBIR will emphasize increased life with the V/M insulation, the improved performance, that is anticipated with this rechargeable battery chemistry, is also likely to permit lower materials cost. Cost remains a key feature to sonobuoy thermal battery deployment, which is to be addressed in the Phase II project.

Future work is based on the InvenTek component technologies, e.g. V/M insulation, thin ceramic fiber separator, CFS, and rechargeable thermal battery chemistry, that were evaluated in the Phase I SBIR as they apply to the 'A' size sonobuoy battery. These evaluations provide hard data to enable system optimization with the Shuster Model at ENSER. The Phase I option provides for a live thermal battery test in the V/M case. We will demonstrate battery designs that are attractive from the optimization modeling results. The primary objective is extending operation time to about 6 h, but we see excellent prospects to concurrently increase thermal battery pulse power/energy by 50%. Additionally, higher power and/or higher energy designs of interest to the Navy can be approached with the other innovative thermal battery components given proof of concept in the SBIR.

The Phase II SBIR supports prototype development of the 6-h thermal battery. As detailed in the Phase II work plan, the advanced thermal battery is developed in close association with ENSER to enable rapid technology transfer and deployment. The Phase II SBIR is a prototype battery design, develop and test project, which includes 20 thermal battery tests at ENSER for the A-size sonobuoy. The plan is to incorporate a V/M case into the initial FY00 build of sonobuoy batteries to meet the 6-h battery life requirement.